Chapter 5

MODELLING THE LOW LATITUDE IONOSPHERE/PLASMASPHERE : A SIMULATED GEOMAGNETIC STORM

5.1 Introduction

The understanding and prediction of geomagnetic storms is currently considered one of the most important problems in solar-terrestrial physics. As discussed briefly in Chapter 1, such storms inject massive amounts of energy into the Earth's atmosphere, energy which may cause damage to satellites and power grids, and interfere with radio communications. The Earth's magnetic field is significantly disturbed allowing increased numbers of high energy particles to enter the magnetosphere. Our understanding of the dynamics of a storm, from its origin in the solar atmosphere, to its interaction with the Earth, is far from complete. However, the study of storms and *'space weather'* in general, has increased in recent years. Spacecraft missions such as Soho, Ulysses and the recently launched Cluster II, are providing increasing amounts of data for analysis and study. In addition, the continually improving sophistication of mathematical models has led to a better theoretical understanding and prediction of stormtime processes.

The work presented in this chapter is a response to features observed in the DMSP dataset during stormtime periods (see Chapter 4 for a description of the DMSP dataset). The phenomenon of a geomagnetic storm is discussed in detail, and a review made of previous work in the field, particularly with reference to low/mid latitude phenomena and the plasmapause. This is followed by a case study of observational data from the DMSP F10 satellite during the major storm of March 24th 1991. Other stormtime data, particularly from June 1991 is also presented, and the observed dominance of the He^+ ion at 800 km altitude during stormtime recovery is discussed. A simulation of the effects of a storm at low latitudes is made using the SUPIM model, and it is shown how changing simple parameters within the model can produce features similar to those observed by DMSP F10.

As stated in Chapter 1, direct evidence for a sudden drop in electron concentration at an altitude greater than the O^+/H^+ transition altitude was originally made by whistler measurements (Carpenter, 1963; 1966; 1967; 1970; Park, 1970; Carpenter et al., 1972), by satellite observations (Taylor et al., 1968; Chappell et al., 1970) and by a combination of both (Corcuff et al., 1972; Carpenter and Chappell, 1973). Electron concentration is observed to fall by a factor of 10-100 in the region L=3-6 and this boundary is known as the plasmapause (Figure 5.1a). The plasmasphere as a whole, is known to extend significantly in the dusk sector (Carpenter et al., 1993), a feature known as the *duskside bulge* (Figure 5.1b).
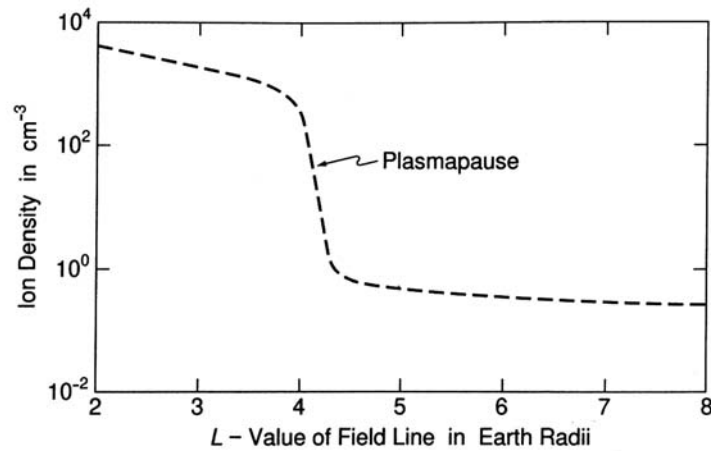
Figure 5.1a. The typical fall in concentration that signifies the plasmapause boundary. This feature is generally observed around L=4 during quiet periods, but may be observed as low as L=2 during severe storms (taken from Baumjohann and Treumann, 1997).
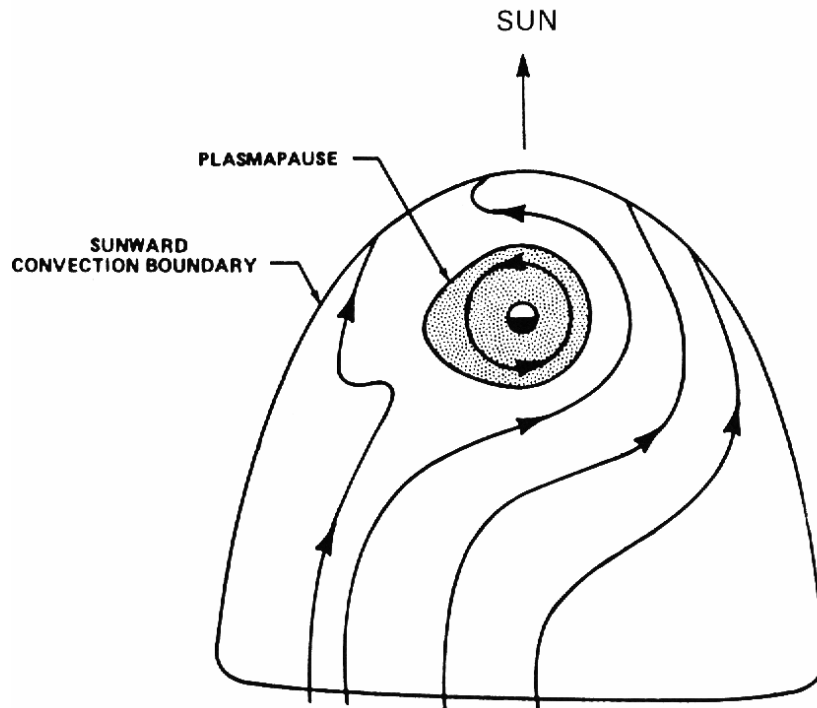

Figure 5.1b. This figure shows the asymmetry of the plasmasphere. A significant extension of the plasmasphere in the dusk sector is known as the 'duskside bulge'. Plasma convection outside of the plasmapause is also indicated (taken from Hargreaves, 1992).

A review of the early plasmasphere/plasmapause studies has been made by Carpenter and Park (1973) and a review of the inner magnetosphere, and its dynamics has also been presented by Russell and Thorne (1970). The thermal structure of the plasmasphere has been detailed by Comfort (1996). Using data from the DE-1 satellite

Comfort (1996) shows that photoelectrons do not always provide sufficient heat to produce the observed ion temperatures. As discussed in Chapter 2 this has led to further investigation of the interaction between the 'hot' ring current population, and the 'cold' plasma of ionospheric origin. The author also proposed the possibility of a modified thermal conductivity, as discussed in Chapter 3.

The depletion in electron concentration known as the mid latitude trough is located in the vicinity of the plasmapause, and although the two phenomena are likely to be linked, there are significant differences between them. Extensive reviews of the mid latitude trough (and ionisation troughs in general) have been carried out by Moffett and Quegan (1983) and Rodger et al. (1992). Since the mid latitude trough is 'usually' observed to be a nighttime only phenomenon, discussion in this current work refers to the *drop in ionisation associated with the plasmapause* and plasmasphere dynamics in general.

Recent work on the plasmasphere has been carried out by Elphic et al. (1996) who discuss the evolution of plasmaspheric ions with respect to an increase in the geomagnetic activity. Elphic et al. (1997) have examined the outer plasmasphere as plasma is stripped away sunwards during the early part of a magnetic storm. This plasma is then swept tailwards by the IMF field lines. As such, large amounts of relatively low energy plasma are predicted to be present in the magnetotail during disturbed periods. Clilverd et al. (2000) have used southern hemisphere VLF receivers to infer unusually low plasmaspheric compositions near L=2.4. Modelling calculations were then performed to rule out flux tube drifting as a mechanism for the depletions. As expected, erosion of the plasmasphere was found to be strongly linked to an increase in magnetic activity.

The approximate location of the plasmapause during the post-midnight hours may be found from the relation

$$L = 5.7 - 0.47 \; K_p^{max} \tag{5.1}$$

(Carpenter and Park, 1973), where L is the equatorial distance to the plasmapause in Earth radii, and K_p^{max} is the maximum value of the K_p index during the preceding 12 hours (Bartels et al., 1939).

5.2 Geomagnetic Storms

5.21 Introduction

As stated above, magnetic (or more properly *geomagnetic*) storms are characterised by a huge increase in the energy entering the Earth's magnetosphere, and by a significant perturbation of the Earth's magnetic field. Magnetic reconnection on the dayside causes an increase in the solar wind particle flux entering the Earth's magnetosphere. For major storms, the entire magnetosphere is initially compressed on the sunward side (Taylor et al., 1968). Enhancement of the ring current occurs as high energy particles from the magnetotail are accelerated inward. Recovery from such storms can take several days. The occurrence of storms is highly correlated with the 11-year solar cycle, and with the 27-day solar rotation period (see Chapter 1, Figure 1.7a/b). During the period around sunspot maximum, storm activity can last for several days or weeks.

In contrast to the low latitude region where the primary energy input remains solar EUV radiation, the high latitude region is also heated by other mechanisms, both of which increase significantly during stormtimes.

- ➢ *Joule heating* occurs due to the difference in velocity between the ion and neutral components of the atmosphere, driven by electric current systems (Foster et al., 1983). It is, in effect, a form of frictional heating. Current systems are enhanced during magnetic storms, and the energy input to the atmosphere via this process may rival or exceed the heating by EUV radiation (Banks and Kockarts, 1973). The additional energy input to the neutral gas may then be transferred to the low latitude region by the neutral wind (Brekke, 1976; Balthazor, 1997).

- ➢ *Particle precipitation* is the deposition of energy in the atmosphere by high energy particles of solar wind origin. During quiet times, a steady flow of such particles is incident on the high latitude atmosphere. Open magnetic field lines allow charged particles direct access to the atmosphere, where they may collide and interact with the neutral and charged particles of terrestrial origin. During stormtime, the increased flux of such particles in the solar wind results in increased precipitation, and thus, increased energy input to the high latitude.

A review of Joule heating and particle precipitation is given by Brekke (1976). A detailed review of geomagnetic storm phenomena within the entire magnetosphere is given by Gonzalez et al. (1994).

5.22 Storm Dynamics and the Dst Index

"...we can define a storm as an interval of time when a sufficiently intense and long lasting interplanetary convection electric field leads, through a substantial energisation in the magnetosphere-ionosphere, to an intensified ring current strong enough to exceed some key threshold of the quantifying storm time Dst index." (Gonzalez et al., 1996).

The strength of a storm is most conveniently determined using the above mentioned *Dst (or Disturbance, Storm Time) index* . This is a measure of the average disturbance of the magnetic field at the equator, and is calculated from hourly measurements made at four low latitude observatories, Honolulu, San Juan, Hermanus and Kakioka. Initially, the northward horizontal component of the Earth's magnetic field, H, is measured and used to calculate a magnetic perturbation amplitude using the quiet time reference field, H_0, and the field created by the current system caused by tidal motion of the atmosphere, H_{sq}. Both H_0 and H_{sq} vary with local time, t´. A mean Dst index is then calculated from the four stations, i, using the formula

$$\text{Dst}(t) = \frac{1}{16}\left(\sum_{i=1}^{4} \cos \Lambda_i\right) \times \left[\sum_{i=1}^{4}\left(H(t) - H_0(t') - H_{sq}(t')\right)_i\right] \quad (5.1)$$

(Baumjohann and Treumann, 1997), where Λ is the magnetic latitude of the station and t is the universal time. The uncertainties in this index result mainly from other sources of magnetic influence.

As stated briefly in Chapter 1, the disturbance in magnetic field during stormtime occurs in three phases. The *initial* or *onset phase* of a storm is characterised by a sudden increase in Dst, typically lasting for a few hours. This is due to an increase in the magnetic field caused by the increased particle flux contained in the solar wind. The magnetosphere is compressed as a result. During the *main phase* of a storm, the strength of the ring current increases. The direction of the magnetic field induced by the ring current opposes the direction of the H component of the geomagnetic field, and the overall field falls rapidly to a minimum. This reduction in Dst typically occurs over a period of about one day. The *recovery phase* of a storm occurs over a number of days and is characterised by the field returning to 'normal' or 'mean pre-storm' conditions. An example of the typical stormtime changes which occur in the Dst index are shown in Chapter 1, Figure 1.8.

5.23 Storms Effects in the Thermosphere

"The thermospheric wind is a response to the heating of the upper atmosphere, and thus it will be altered if additional sources of heating appear" (Hargreaves, 1992).

The first prediction that magnetic storms could change the thermospheric wind was made by Cole (1962). During a storm, the increase of precipitating particles, and the electric current effects in the E region, both increase heat input to the high latitude region. Figure 5.2, taken from Roble (1977), shows model results of the effect of high latitude heating on the circulation of the thermosphere. It is the 'stormtime' circulation pattern that can help transfer the energy incident on the high latitude region into the low latitude thermosphere. The temperature of the neutral constituents can rise by over 1000 K during stormtimes (Rishbeth et al., 1987).
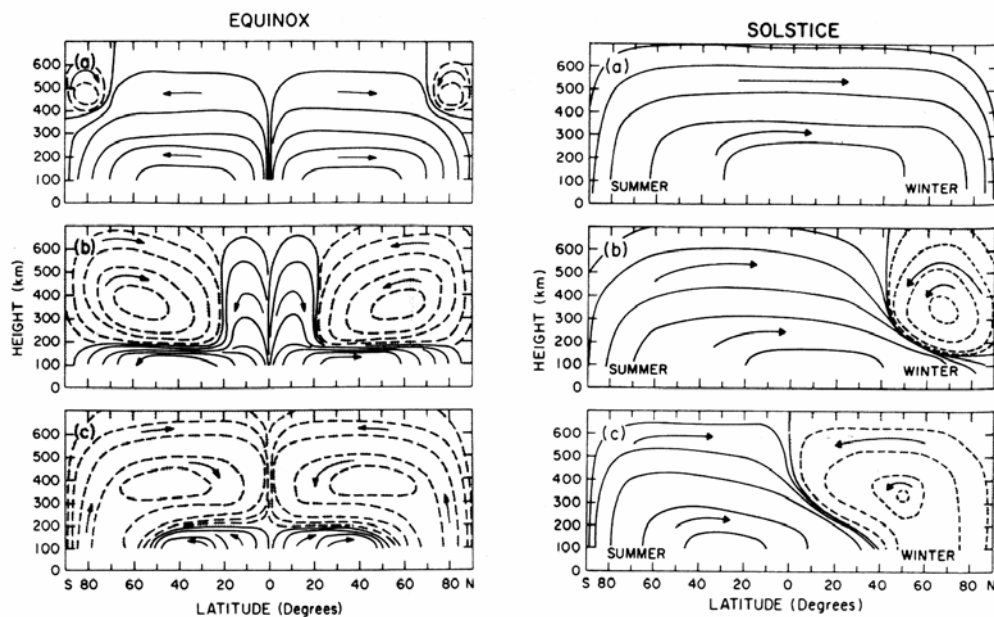

Figure 5.2. Model results of the effect of high latitude auroral heating on the thermospheric circulation. Results are shown for equinox and solstice for a) low, b) average and c) strong magnetic disturbances (taken from Roble, 1977).

The exact transition process between these idealised 'quiet' and 'active' thermospheric wind patterns has not been determined. The circulation pattern may change slowly as heating in the auroral regions increases, and then return to normal as auroral heating decreases. In contrast, since the inertial mass of atmosphere involved is large, once a circulation pattern is established it may remain dominant and only return to *'normal'* over an extended period, or as a result of another large energy input.

Since thermospheric winds can raise or depress the atmosphere, it is expected that altitude dependent changes to the composition will also be observed during stormtimes. Around the solstice periods, the wind blows from summer to winter, and the vertical component of the wind in the summer hemisphere raises the thermosphere. This results in an increasingly *molecular* composition as the heavier atomic constituents are raised to a comparatively higher altitude. In the winter hemisphere, the vertical component of the wind is directed downwards, lowering the thermosphere, and the composition becomes increasingly *atomic*. Changes in the circulation pattern that accompany a magnetic storm will disturb the typical summer/winter compositions described above.

Fuller-Rowell et al. (1996) have shown how the effects of heating in the auroral region can be detected at mid and low latitudes. They show how a *compression bulge* of increased molecular mass is formed in the high latitude region. In the summer hemisphere, this bulge is transported to mid and low latitudes over the day or two following storm onset. In the winter hemisphere, poleward winds restrict the equatorward movement of the bulge. The induced composition changes can affect the nature of the storm in the ionosphere (see Section 5.213)

The effect of composition changes in the thermosphere will also have a resulting effect in the ionosphere. Increasing ionisation of the molecular constituents (e.g. N_2) will occur in regions where the thermosphere is raised. In regions where the thermosphere is depressed, increasing ionisation of the atomic constituents (e.g. O) will occur. In addition, since the chemical reaction rates are to a large part temperature dependent (see Chapter 3), the equatorward extent of auroral heating can, in principle, be traced by the resulting changes in the ionosphere.

5.24 Storms Effects in the Ionosphere

The link between storms in the ionospheric region and the phenomenon of a geomagnetic storm remains unclear. Despite an ionospheric disturbance usually occurring at the same time as a geomagnetic storm, this is not always the case. 'Ionospheric storms' may occur when no disturbance is evident in the Dst index (Hargreaves, 1992), an indication that the mechanisms responsible for each phenomenon are not the same. Despite this, the occurrence of a *initial* phase, followed by a *main* phase and then a *recovery* phase for a geomagnetic storm, also typically occur for an ionospheric storm (see Figure 5.3). Ionospheric storm phenomena are generally more evident in the F_2 region and the three phases correspond to a increase in the peak electron concentration NmF_2 lasting a few hours, a sharp fall in electron concentration, and a slow return to normality over a period of days, respectively. However, behaviour in contrast to the 'ideal' situation described above does occur. Local time plays a significant role in the precise effects detected. The *negative main phase* of the storm (where NmF2 usually drops sharply) is weaker in the afternoon and evening periods, and stronger in the nighttime and morning. The positive phase of the storm (where

NmF2 initially increases) may be reduced, or even non-existent, during the nighttime. A statistical study of the F region stormtime changes, and apparent local time effects has been made by Hargreaves and Bagenal, (1977).
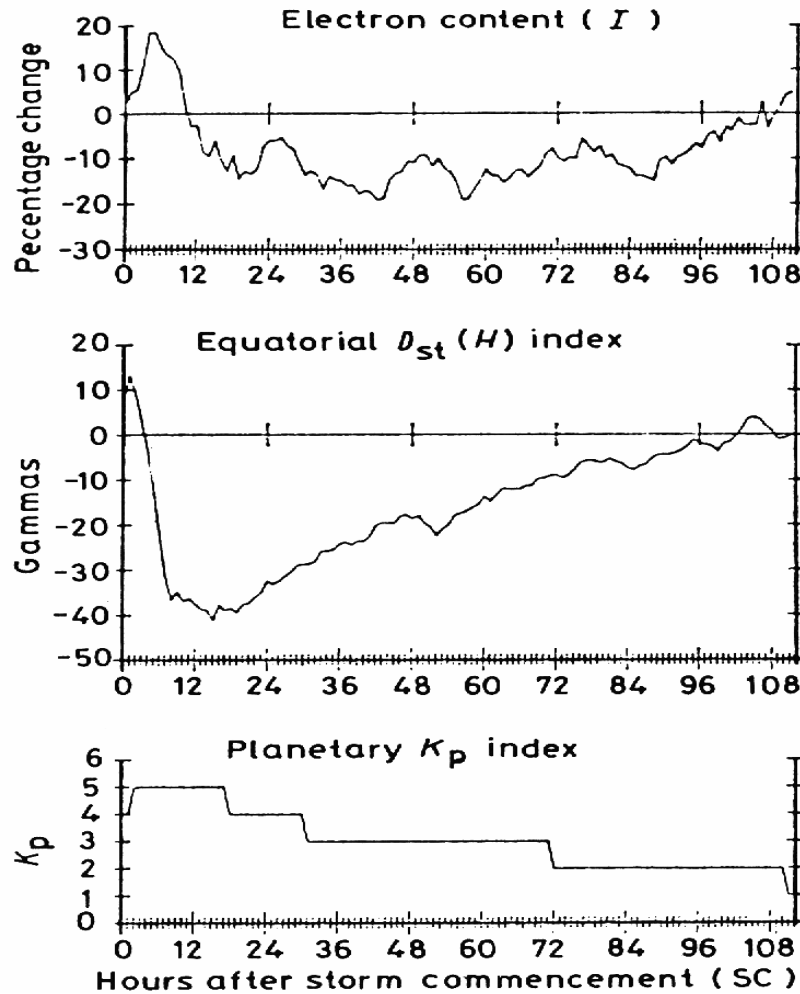

Figure 5.3. The average stormtime variations of electron content and Dst. This figure shows the close relation that sometimes occurs between the ionospheric and geomagnetic storm. (Taken from Mendillo, 1973).

Another contrast to the 'ideal' ionospheric storm occurs when the electron concentration may persist at the higher levels associated with the initial phase. Such behaviour is termed a *positive main phase*. This type of behaviour is found to occur during the winter period at low latitudes, particularly in the southern hemisphere. Rodger et al. (1989) used F region data to show the effects of a storm are strongly dependent on season. Storm data from three stations in the southern hemisphere taken between 1971-1981 were used to determine the seasonal and local time variation of the peak electron concentration in the F_2 layer (NmF_2). An explanation of the observations was proposed based on a combination of an 'AC' and a 'DC' effect. The AC effect is the diurnal variation, and the DC effect is the 'mean' variation of NmF_2. It was proposed that the AC effect is caused by the effects of the neutral wind, and the subsequent changes in momentum exchange between the ion and neutral gases. Variation in the DC effect is

attributed to direct energy input to the mid latitude region during stormtimes.

In addition, Rodger et al. (1989) showed that positive storms were more prevalent during the winter. Negative storms were found to be more prevalent during the summer, when hardly any increase in NmF_2 was observed, at any local time. One explanation of this effect has been made by Fuller-Rowell et al. (1996). As stated above, the movement of a composition bulge of increased mean molecular mass passes to mid and low latitudes (in the summer hemisphere) during the day or two following a modelled storm. Since the ionospheric production rate is linked to the atomic concentration, and the loss rate is linked to the molecular concentration, an increase in mean molecular mass will reduce NmF_2, giving a negative storm. In contrast, a decrease in mean molecular mass increases the likelihood of a positive storm.

5.25 Storms Effects in the Plasmasphere

As with all other regions of the magnetosphere, the occurrence of a geomagnetic storm causes significant changes in the plasmasphere, and particularly in the location of the plasmapause boundary. The location of the plasmapause boundary is typically characterised by a sharp drop in the electron concentration. This feature is typically located close to L=4 (during quiet times).

The dynamics of the plasmasphere as a whole are strongly affected during a geomagnetic storm. During quiet periods the plasmasphere co-rotates with the Earth whilst the field lines at higher latitude respond directly to the solar wind. The boundary between the field lines controlled by co-rotation, and the field lines which move according to the magnetospheric electric field convection patterns is thought to occur at the plasmapause, a prediction first made by Nishida (1966). During a storm, observations have shown that the drop in electron concentration associated with the plasmapause boundary occurs closer to the Earth (Park, 1974). For major storms, the plasmapause has been found as low as L=2.2 (Brace et al., 1974). The cause of this inward motion of the plasmapause is thought to be penetration of magnetospheric convection to lower latitudes (Saxton and Smith, 1992). Regions of high concentration plasma before the storm, are moved, under the influence of convection, to the outer magnetosphere as demonstrated by Chappell et al. (1971a/b). The details of this mechanism are beyond the scope of this thesis, but the result of the process is to deplete the inner magnetosphere. Model calculations of this effect are shown in Figure 5.4.

Case studies into the effect of significant geomagnetic storms on the plasmasphere have been undertaken by numerous authors including recent work by Carpenter et al. (1992), Richards et al. (1994) and Jirícek et al. (1996). In addition, Chi et al. (2000) have used ground magnetometer stations close to L=2 to analyse how the plasmasphere was depleted and refilled during the magnetic storm of 25th September, 1998 . Plasma concentration was observed to drop to 25% of the pre-storm value and the total electron content inferred from GPS (Global Positioning System) signals was observed to drop by 60%.

The refilling of previously depleted flux tubes occurs during the recovery phase of a storm, as particles of ionospheric origin flow upwards from the F region into the depleted topside. This refilling will obviously occur most strongly during the daytime since that is when the ionospheric concentration is greatest, and the upflow to the

topside is also high. The time period for recovery is strongly dependent upon the flux tube volume, and thus on the L value of the tube (Park, 1974; Kersley et al., 1978; Kersley and Klobuchar, 1980).
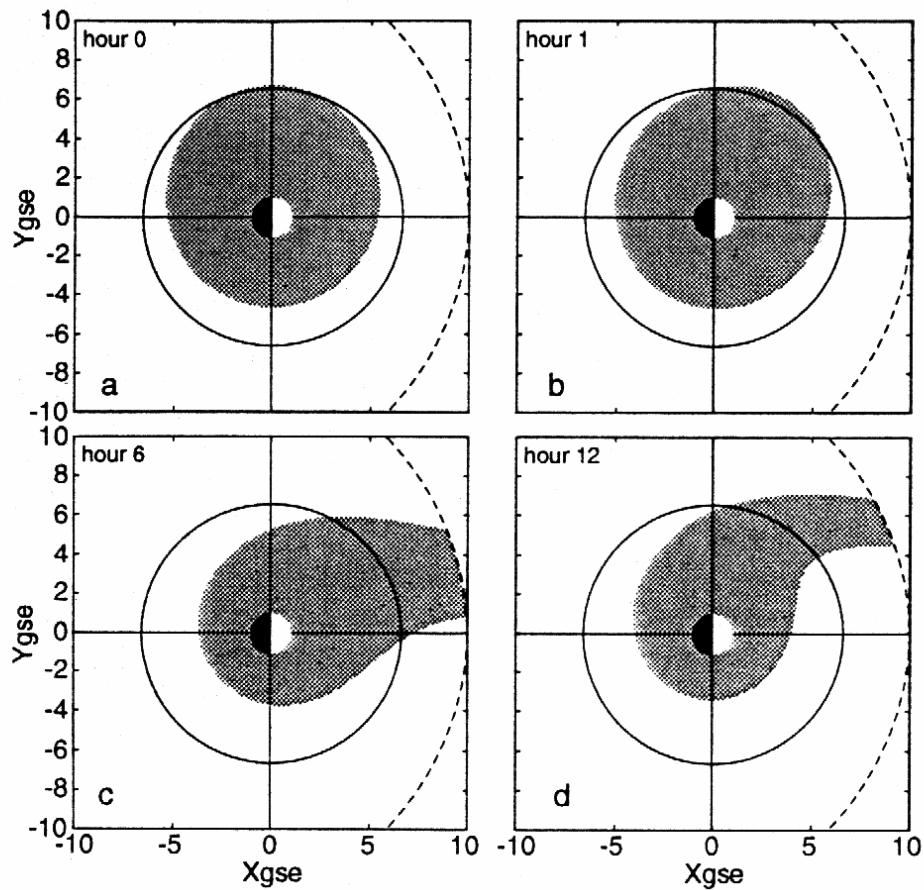

Figure 5.4. Model calculations of plasmaspheric stormtime erosion when a large convective electric field is suddenly applied to the magnetosphere. The motion of flux tubes becomes influenced by convection, and plasma is swept out of the region of co-rotation. (Taken from Elphic et al., 1996).

Recent modelling work on refilling of plasmaspheric flux tubes has been carried out by Singh and co-workers (Singh et al., 1986; Singh and Hwang, 1987; Singh and Torr, 1990; Singh, 1991; Singh and Horwitz, 1992). By solving time-dependent hydrodynamic equations they predict the formation of collisionless shocks during refilling, a mechanism initially postulated by Banks et al. (1971). However, the constraints placed upon such shock formation ($T_e > 3T_i$) indicate that shocks will only occur infrequently, if at all. The prediction of shock formation when $T_e \approx T_i$ has also been made, but calculations have yet to be performed regarding the validity of this theory. In addition, no observational data has yet been presented showing evidence of shock formation during flux tube refilling.

Lin et al. (1992) and Wilson et al. (1992) have used a semi-kinetic model to investigate the process of refilling the plasmasphere. They have investigated the effects of

Coulomb collisions and wave-particle interactions on the refilling process. Wilson et al. (1990) conclude that the thermal plasma along the L-shells 3, 4, 5 and 6 returns to an isotropic state after between 6 and 30 hours. However, the simulation was halted before the tubes reached a state of dynamic equilibrium. This result may be compared with the results of Kersley and Klobuchar, (1980) who performed protonospheric content measurements using signals from the ATS-6 satellite. They found that recovery to mean levels of concentration took between 6 to 8 days. However, complete refilling to conditions of dynamic equilibrium did not occur until after two weeks of quiet conditions.

The occurrence of storm activity is not linear with time, but closely follows the 11 year solar cycle. Around solar minimum, storm activity is infrequent, but close to solar maximum, disturbances are frequent, and the magnetosphere can remain disturbed for months at a time, as a succession of storms impinge on it. During such times, it is likely that flux tubes of large volume never fully recover to the 'normal' conditions observed during extended quiet periods. Instead, refilling and depletion of flux tubes will progress constantly as a series of storm disturbances occurs.

5.3 Data Analysis – The March 24th 1991 Storm : A Case Study

5.31 Introduction

The severe magnetic storm which began on the 24th of March, 1991 was observed by the DMSP F10 satellite, from storm commencement around 03:00 UT through the recovery phase which lasted in excess of six days. The instrumentation, orbital characteristics and mission objectives of the DMSP program have been discussed previously in Chapter 4. The progress of the storm can be seen by examining the Dst plot for the duration of the storm which is shown in Figure 5.5. Examination of the changes in the plasma temperature and composition that occur during this equinoctial storm, may be compared with the changes that occur during the solstice storm periods that occur in June, and are discussed later.

Storm onset occurs around 03:00 LT on the 24th March. As can be seen, Dst was slightly negative, and broadly constant, during the preceding day. At storm commencement, the increase in solar wind pressure causes Dst to increase sharply to an index of approximately +60 nT. As the ring current is enhanced, an induced magnetic field is created, which opposes the direction of the Earth's magnetic field. Thus, Dst drops to a minimum of around -300 nT, approximately 21 hours after the initial storm commencement. The recovery period which occurs over the next seven days is interspersed with further bursts of activity, causing more fluctuations in the Dst index. Continued disturbances to the Dst index were observed to follow the recovery period which continued until the 30th March.
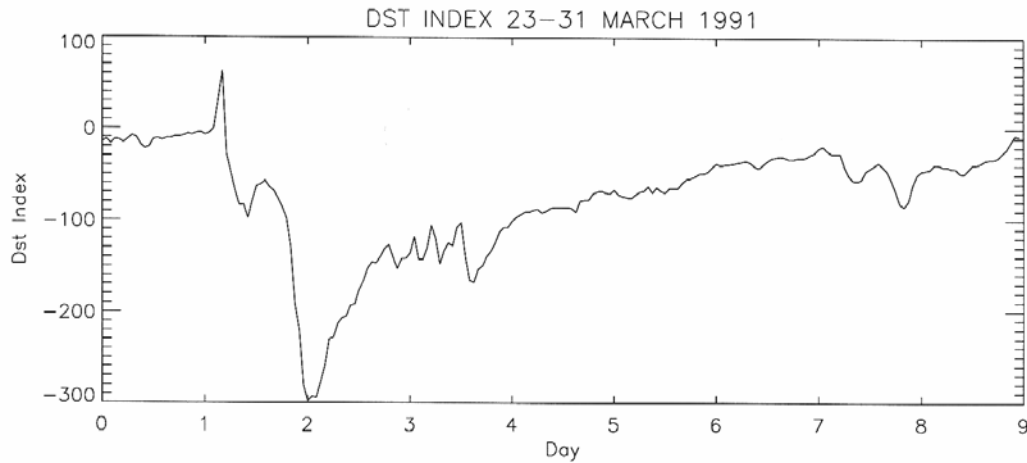
Figure 5.5. The hourly Dst profile from 23rd March until 30th March. Storm onset occurred around 03:00 UT on 24th March. (Data from World Data Centre C1 at RAL).

5.32 Data Analysis and Results

The Retarding Potential Analyser (RPA) and Langmuir Probe (LP) instruments on board the F10 satellite were in constant operation during the storm period. The orbital period of the satellite was around 105 minutes, resulting in almost 14 orbits per day each separated in longitude by just over 25° (see Chapter 4 for further details). Changes in the electron and ion temperatures, and the ion concentrations are evident from storm onset, and data from the three orbits surrounding storm onset (denoted PRE-STORM, STORM 1 and STORM 2 respectively) are shown in Figure 5.6.

Before storm commencement (PRE-STORM) the electron and ion temperatures were fairly constant with respect to magnetic latitude, with values close to 3000 K and 2500 K respectively. The O^+ ion was dominant with a minima in concentration centred around the magnetic equator. The total ion concentration was fairly constant around 1×10^5 cm^{-3}. The H^+ and He^+ ion concentrations were highest close to the magnetic equator. The He^+ ion had a maximum concentration around 3×10^4 cm^{-3}. The H^+ ion concentration was lower than this and both the lighter ions were close to the limit of detectability for the RPA instrument in the mid latitude region. At high latitude regions, the H^+ and He^+ concentrations were so low as to be undetectable by the RPA. Storm onset actually occurred during the nighttime DMSP pass between the PRE-STORM and STORM 1 data-sets. Thus STORM 1 actually corresponds to the orbit which occurred approximately thirty minutes after the storm commencement.

The major difference between the PRE-STORM and STORM 1 temperature profiles is the sharp rise in electron temperature, T_e, that occurs in the mid to high latitude regions. This is caused by the sudden increase in heating due to enhanced high latitude particle precipitation. The peak electron temperature reaches 5700 K and occurs around ±55° magnetic latitude. The low latitude electron temperature also rises to around 4000 K close to the magnetic equator.
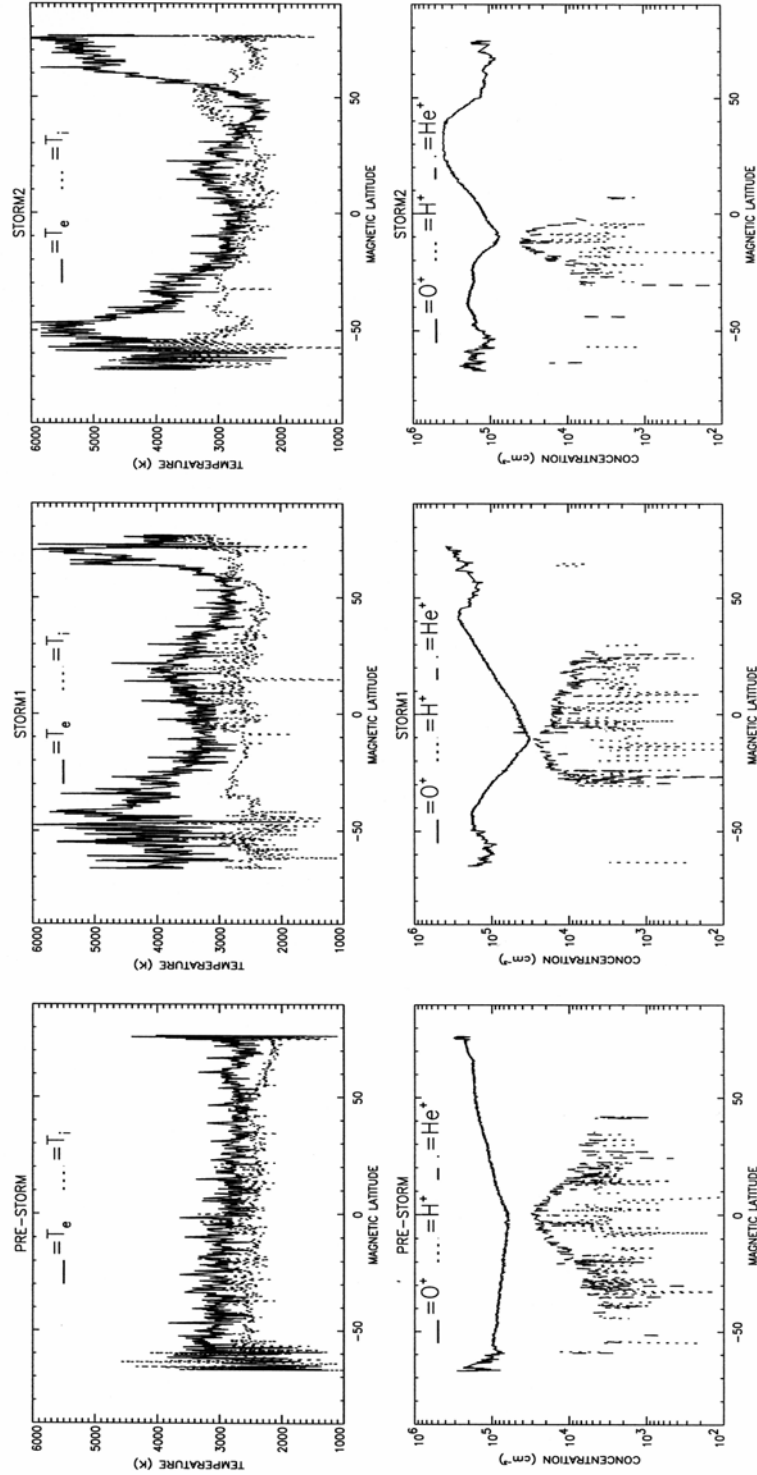
Figure 5.6. Plot showing the raw DMSP F10 data on the 24th March 1991 at around 800 km altitude and 09:00 LT. The figure shows the electron and ion temperatures and the O^{+}, H^{+} and He^{+} ion concentrations for the three daytime orbits on either side of storm onset, labelled PRE-STORM, STORM 1 and STORM 2 respectively. The spacecraft orbit was in the north-to-south direction.

During the STORM 2 orbit, the peak in T_e reaches almost 6000 K. In contrast, the ion temperature, T_i, only rises slightly in the mid latitude region, to a peak of around 4000 K. However, during further orbits on the same day, T_i reaches a peak of almost 5000 K (figure not shown). This probably corresponds to heat transfer between the electron and ion gases, and between the ion and neutral gases. Also, the ion thermal conductivity is much less than the electron thermal conductivity. Thus, energy input to the ion gas that occurs in the D, E and F regions of the ionosphere, will take longer to be transferred to the topside, than the corresponding energy input to the electron gas.

Another dramatic change occurs in the total ion concentration, N_i, between the PRE-STORM and STORM 1/STORM 2 orbits. Peaks in N_i occur in the northern and southern hemispheres (with maxima around 1.5×10^5 cm^{-3}), initially centred on around $\pm 50°$ magnetic latitude (figure not shown). This is also due to the increase in particle precipitation, that accompanies a magnetic storm, and the corresponding increase in ionisation in the high latitude region. It should be noted that these peaks in maximum ion concentration move equatorward to around $\pm 30°$ magnetic latitude during the following twenty-four hours (figure not shown). Changes in the individual ion concentrations, and their relative abundances also occur between the PRE-STORM and STORM1/STORM2 orbits. Before the storm, O^+ is the dominant ion, whilst H^+ and He^+ are minor ions. During the storm, the trough in O^+ concentration close to the equator initially deepens (STORM1), and the He^+ ion concentration approaches that of O^+ at around 3×10^4 cm^{-3}. As the storm progresses (STORM2), this situation changes and the O^+ concentration close to the equator increases back to around 1×10^5 cm^{-3}. Peaks in the O+ concentration occur in the mid to high latitude region, again due to the increase in particle precipitation that accompanies a magnetic storm.

Figure 5.7 shows DMSP data from three consecutive orbits that took place during the recovery period of the storm. By this time the high latitude heating has diminished considerably, and the peak electron temperature has dropped to around 4000 K, at a magnetic latitude close to $\pm 50°$. This is a result of the 'relaxation' of the magnetospheric convective electric field poleward. The plasmasphere has expanded, and the auroral heating region has moved poleward. The ion temperature remains fairly constant with respect to magnetic latitude, at around 2500 K, but signs of localised heating remain present in the high latitude region. The total ion concentration during these orbits is fairly constant at low to mid latitudes, becoming more variable above around 50°. On the RECOVERY 3 orbit, the He^+ ion concentration again approaches that of the O^+ ion, at around 4×10^4 cm^{-3}. This behaviour seems to be the result of a depletion (or trough) in the O^+ concentration, rather than an enhancement in the light ion concentration.

5.33 Discussion

The storm of March 23rd, 1991 has been studied using data from the DMSP F10 satellite. In many ways, the storm occurs under conditions that approximate to an 'ideal' storm, since the disturbance occurs close to the equinox and seasonal variability is avoided. In addition, the previous weeks had been fairly quiet with reference to the geomagnetic conditions, and although small disturbances took place during the recovery period, no further severe storms occurred until after the return to 'normal' conditions (as measured by recovery of the Dst index).
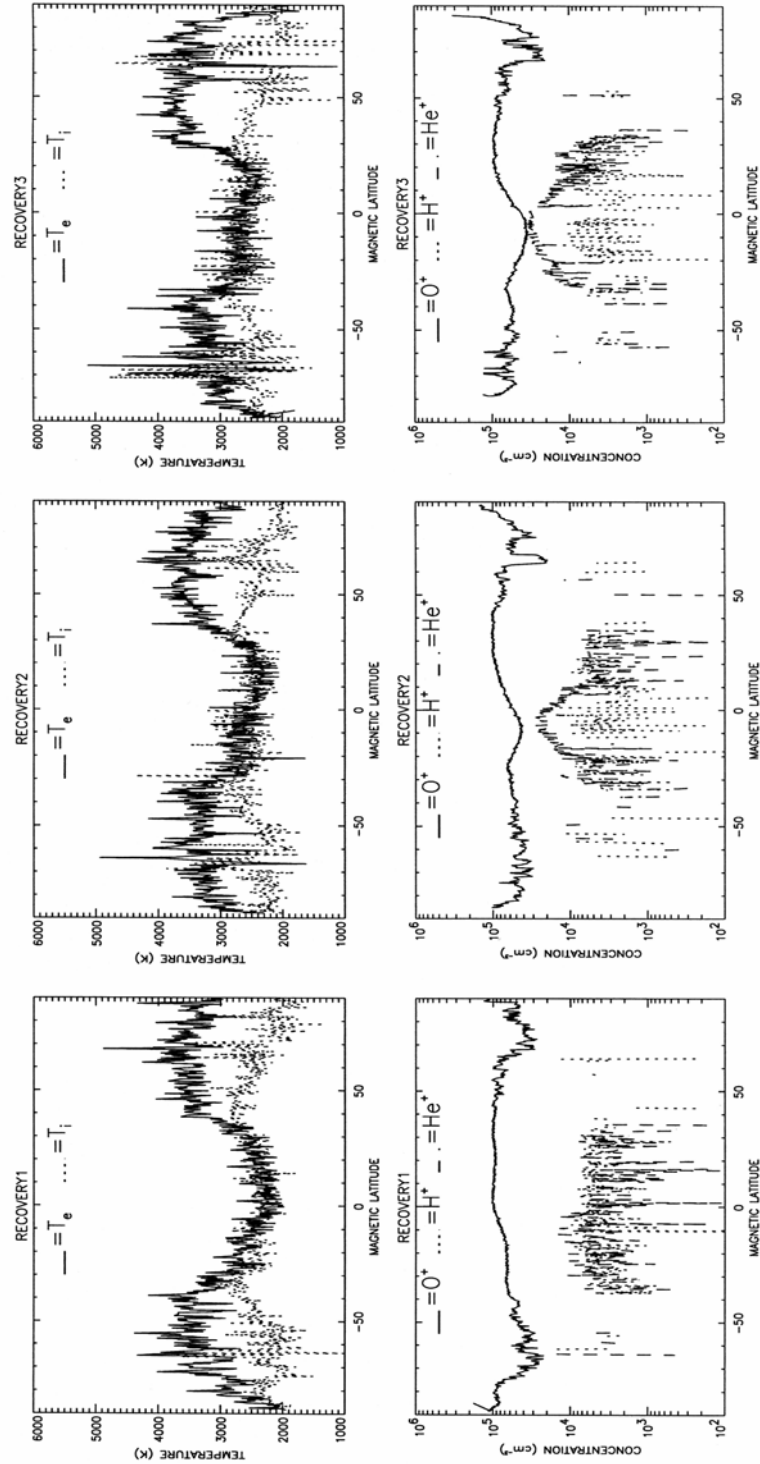
Figure 5.7. Plot showing the raw DMSP F10 data on the 27th March 1991 at around 800 km altitude and 09:00 LT. The figure shows the electron and ion temperatures and the O+, H+ and He+ ion concentrations for the three final three orbits on this day, labelled RECOVERY 1, RECOVERY 2 and RECOVERY 3 respectively.

As expected, there are large amounts of heat input to the high latitude region during the storm, signified by the sudden increase in the thermal electron temperature. This increase is due particularly to the enhanced particle precipitation. The total ion concentration is also increased as a result of this effect. Changes in the individual ion concentrations are less easy to explain. The peaks in O^+ concentration that occur in the high latitude region, are likely to be due directly to increased particle precipitation, and thus increased ionisation. At low and mid latitudes, there are occasional depletions in the O^+ concentration close to the magnetic equator during both the storm orbits, and during the recovery period. Such depletions allow the He^+ concentration to approach that of O^+. This effect is similar to that which occurs in the June 1991 data, and is reasons for it are discussed later in this chapter.

During the recovery period, energy input to the high latitude region falls from a stormtime maximum, and the electron and ion temperatures also begin to fall. In addition, the elevated ion concentration also drops as ionisation by particle precipitation is reduced. The peaks in plasma temperature and concentration move poleward as the pressure exerted on the magnetosphere drops, and the auroral region moves back to higher latitudes. To summarise, the storm of March 24th, 1991, was in many ways, an ideal example of a 'textbook' major geomagnetic storm. The observed changes in plasma parameters that were measured around 800 km altitude by the F10 satellite may be used as a base with which to compare features measured by the satellite, at other times.

5.4 Data Analysis – Stormtime Effects During June 1991

5.41 Introduction

The months of May and June 1991 occurred close to the maximum activity period of the solar cycle, and thus, during the time when major geomagnetic storms were most likely. The solar and geomagnetic activity for these months are shown in Figure 5.8. As can be seen, almost the entire month of June was severely disturbed. Three X-class solar flares occurred in early June and subsequent sudden storm commencements were observed on the 4th, 8th, 9th and 10th of the month (Pavlov et al., 1999). The period between 5-11th June has been considered as a single storm interval and has been the subject of previous experimental and theoretical investigations. (Pavlov et al., 1999). The month of May 1991 will be considered as being of typical mean activity for this period of the solar cycle. Although there are significant disturbances throughout the month, at no time does the Dst index fall below around -50 nT. In contrast, severe disturbances occur during the month of June, with much of the month being either disturbed, or undergoing 'recovery' from disturbed conditions. The largest storms occurred between the 4th and the 11th of June.

5.42 DMSP Observations of He^+ Dominance Around 800 km Altitude

The importance of singly ionised helium, He^+, in the topside ionosphere was originally proposed as a result of theoretical work by Hanson (1962). Satellite observations have

since confirmed regions where He$^+$ is the dominant ion, or the dominant light ion, where the light ions are H$^+$ and He$^+$ (Taylor et al., 1970; Hoffman et al., 1974; Heelis et al., 1981).
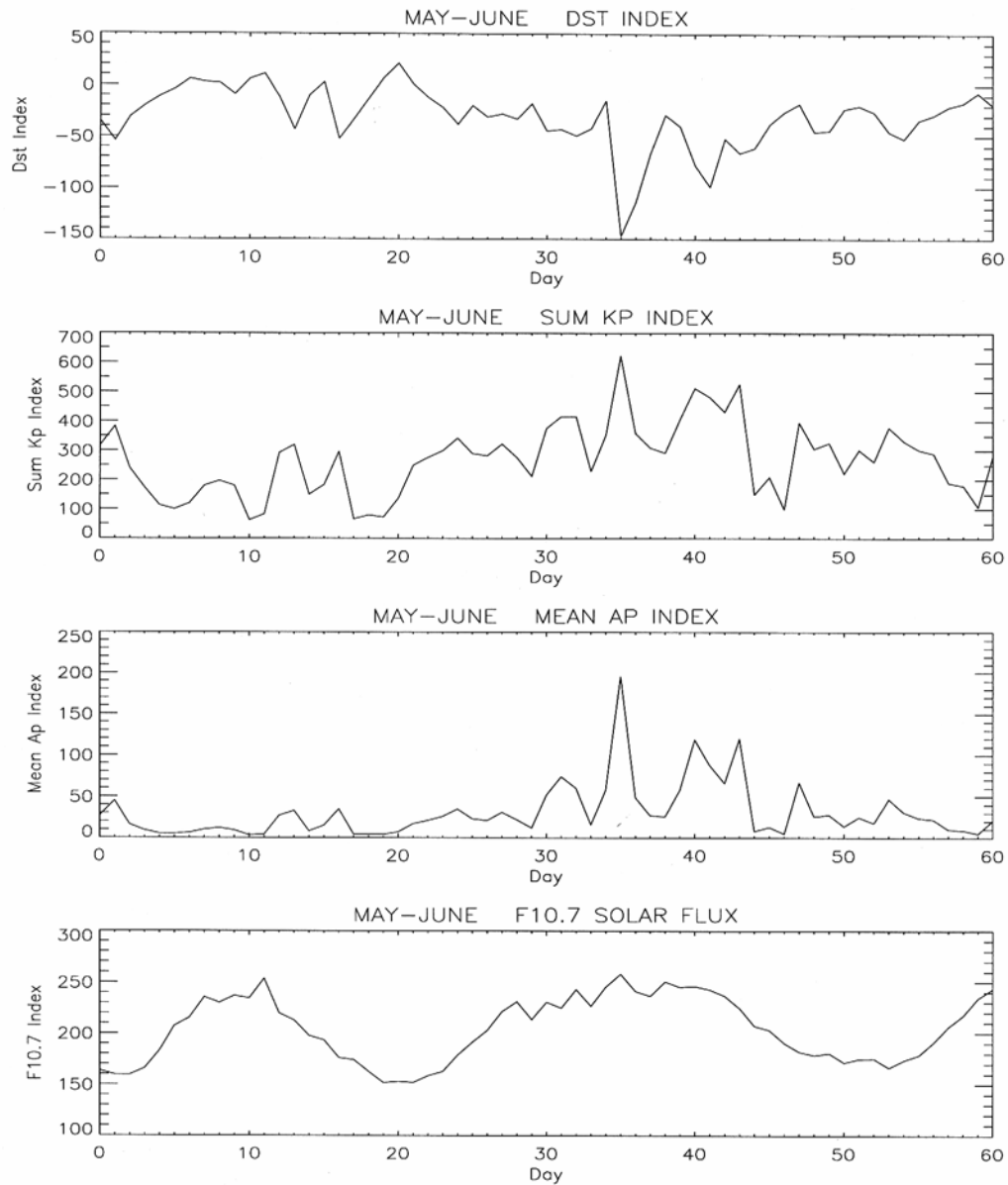

Figure 5.8. Plot showing the a) Dst index, b) daily sum of the 3 hourly Kp index, c) daily mean Ap index and d) the F10.7 index, for the months of May and June 1991. (Data from World Data Centre C1 at RAL).

Experimental and theoretical studies have quantified the expected distribution and behaviour of He$^+$ (e.g. Paresce et al., 1974; Murphy et al., 1979; Quegan et al., 1984; Chandler and Chappell, 1986; Newberry et al., 1989; Moffett et al., 1989; Bailey and Sellek, 1990;   Heelis et al., 1990; Bailey and Sellek, 1992), generally during magnetically quiet conditions. Paresce et al. (1974) compared data from a sounding rocket with model calculations of He$^+$ concentration. The authors found the best fit to

the observational data occurred when the model plasmaspheric He^+ was in diffusive equilibrium and had an altitude-temperature gradient of 0.5 K km^{-1}. The model calculations showed that the concentration of He^+ was expected to become constant in the altitude region between 1 and 2 Earth radii.

Quegan et al. (1981) were the first to provide the mathematical formulation which allowed He^+ to be included in a fully ionised, four-component plasma. Model results by Quegan et al. (1984) showed that regions of He^+ dominance can occur in the high latitude topside ionosphere, and the behaviour of He^+ in this region is largely determined by plasma convection. The authors postulated four conditions, any of which could lead to regions of He^+ dominance. Although these conditions were deduced in study of the high latitude topside region, they are given below, since they are useful to compare with the regions and conditions examined in the current study.

> *"(i) Both O^+ and H^+ must be depleted. This implies lack of exposure of the F-region to sunlight and any other cause of ionisation.*
>
> *(ii) There must be sunlight on the topside ionosphere region of the upper atmosphere, acting either to maintain He^+ concentrations or to cause a rapid enhancement in He^+.*
>
> *(iii) Transit through a region satisfying condition (ii) must not be too fast, so that He^+ has enough time to build up, while O^+ and H^+ are still at low abundances or decaying.*
>
> *(iv) The decay region for O^+ and H^+ and the region of He^+ dominance need not be in the same place. Depleted plasma convecting into a region satisfying condition (ii) can produce a region of He^+ dominance."*
> (Quegan et al., 1984).

These conditions will henceforth be referred to as *'the Quegan et al. conditions'*.

Chandler and Chappell (1986) analysed DE 1 satellite data, and found typical field-aligned velocities of H^+ and He^+ of a few hundred metres per second. Observations of field-aligned velocities close to 1 km s^{-1} were attributed to refilling of the plasmasphere. Counter-streaming of H^+ and He^+, where H^+ was flowing down the field line, and He^+ was flowing up the field line, was also observed.

Bailey and co-workers have previously used versions of the SUPIM model, coupled with observations, to analyse the behaviour of He^+ at low and mid latitudes (Bailey and Sellek, 1990; Heelis et al., 1990; Bailey and Sellek, 1992). Model calculations have quantified the flows of H^+ and He^+ at solar maximum, in both the winter and summer hemispheres, during the day and night. Counter-streaming of H^+ and He^+ is predicted to be most likely to occur when tube content is relatively low. When tube content is high, counter-streaming is less likely to occur, and takes place over smaller regions of the tube.

Little previous discussion has been made of the role of He^+ during stormtimes. Horwitz et al. (1984) presented results from the DE 1 satellite during the storm on the 12th of November, 1981. After the time of maximum disturbance, He^+ is observed to become

the dominant ion as the concentration of other ion species measured by the satellite (H^+, O^+, He^{++} and O^{++}) drops below that of He^+ (in the region L>3.5). This is an indication that either (a) He^+ is not depleted when the outer plasmasphere is eroded (unlikely since He^+ is constrained by the magnetic field to move along with other charged particles), or that (b) He^+ recovers and refills quicker than the other ions.

The importance of He^+ to the development of electromagnetic ion cyclotron (EMIC) waves in a H^+/He^+ plasma has been investigated by Young et al.(1981) and Roux et al. (1984). In the presence of He^+ ions, an EMIC wave may trap thermal electrons, and heat them to superthermal energies between 3 and 20 eV (further discussion of EMIC waves is beyond the scope of this thesis).

Regions of He^+ dominance are observed in the DMSP F10 dataset, particularly during the storm/recovery periods that occur during June 1991. Examples of such features are shown in Figure 5.9. Further similar examples are found throughout the month of June. The figure shows a selection of the orbits where He^+ is the dominant ion, or is close to being the dominant ion. Due to the summer-to-winter neutral wind, the F region is elevated in the northern hemisphere and depressed in the winter hemisphere. At 800 km altitude, this has the effect of increasing the O^+ concentration in the northern hemisphere and reducing its concentration in the southern hemisphere. It is clear from Figure 5.9, that the regions where He^+ dominance occurs are caused by a fall in the O^+ concentration and are not due to an enhancement in He^+. Such regions are only seen in the winter (southern) hemisphere during June 1991, and are typically observed between 10°S and 55°S magnetic latitude.

The increased depletion of O^+ that occurs during disturbed periods is proposed to be due to erosion of the plasmasphere. At a constant altitude of 800 km, the relative O^+ concentration will be observed to fall in the winter hemisphere, as the F region is depressed by the neutral wind. However, further depletion of O^+ will occur as flux tubes that were previously co-rotating, and 'filled' with ions of ionospheric origin, become affected by the magnetospheric convective electric field during stormtimes. Such flux tubes may stop co-rotating, and follow paths where conditions will significantly reduce tube concentration (see Figure 5.1b and Figure 5.4).

5.43 Discussion

Observations during the geomagnetically disturbed month of June 1991 show regions close to 800 km altitude, at 09:00 LT, where ionised helium is at a higher concentration than either ionised oxygen or ionised hydrogen. This feature is only observed in the winter (southern) hemisphere between -10° and -55° magnetic latitude. In addition, the feature is much more evident in the regions when recovery from geomagnetic storm is likely to be occurring.

The main anomaly to consider when formulating an explanation of the observations made throughout the period January to June, 1991, is the presence of regions where the relative He^+ concentration is increased during apparently geomagnetically quiet periods. These regions appear to occur randomly throughout the year. During the 14/15 orbits per day that are made by the F10 satellite, one or two occasionally show regions where the O^+ concentration decreases and thus, the relative H^+ and He^+ concentrations increase.
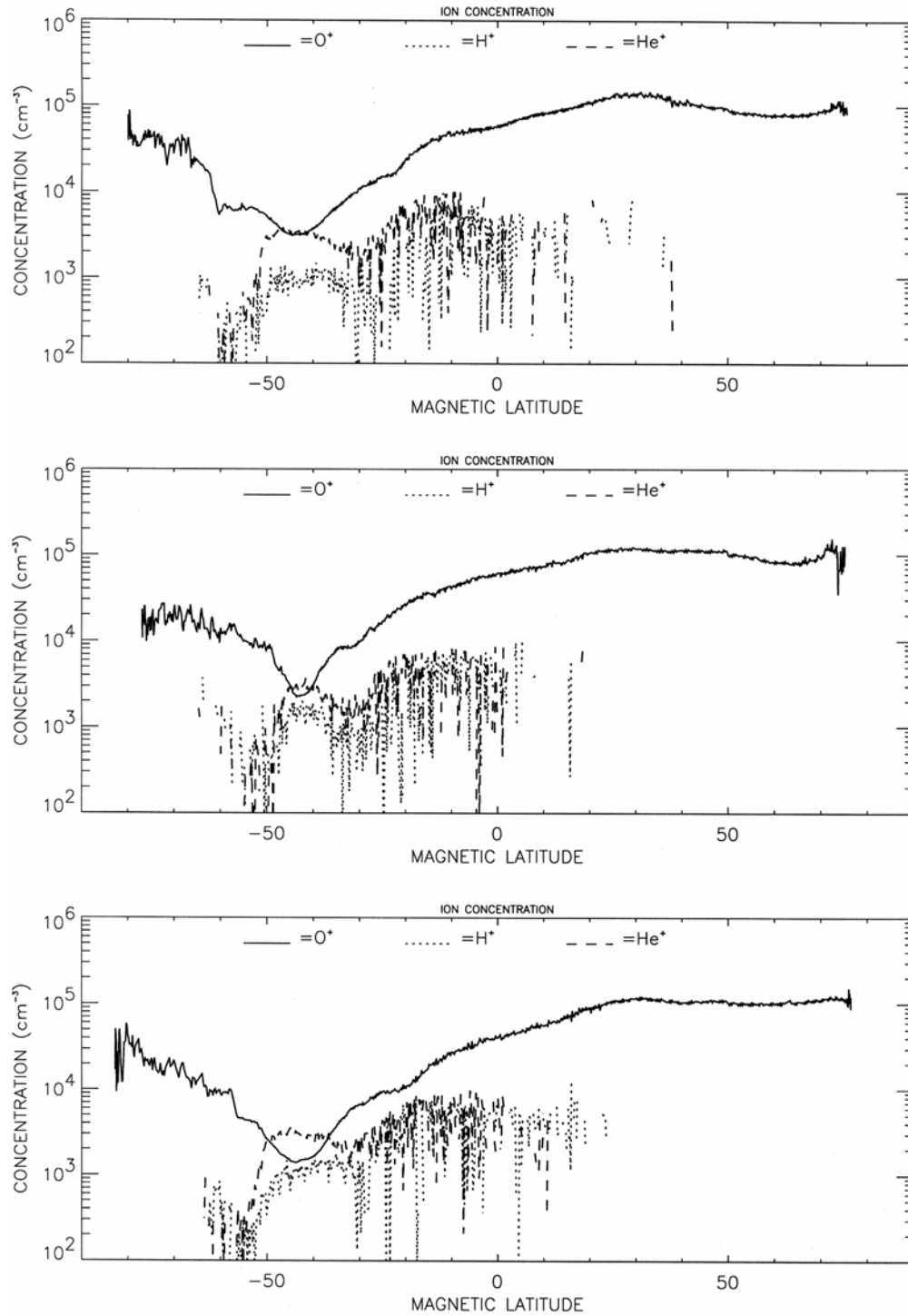
Figure 5.9. Examples of regions where the He⁺ ion is the dominant, or close to the dominant ion, during the month of June 1991. The orbits shown are from the 4th, 22nd and 29th of June respectively.

The occurrence of this feature does not seem to be linked to any of the parameters which are known to affect plasmasphere dynamics, e.g. season, longitude, local time, solar or magnetic activity, and it remains unexplained. However, the observation of the regions where He^+ becomes the dominant ion during the recovery phase of a geomagnetic storm are more extended in latitude, and He^+ becomes more dominant, compared with the quiet time observations of this feature. This indicates a strong link between stormtimes and the regions of He^+ dominance

The occasional presence of two troughs in the O^+ concentration in the mid latitude region (figure not shown), may indicate the passage of the satellite through separately detached regions of plasma. As the satellite orbits from northern hemisphere, it passes from the high concentration region of co-rotating plasma, into a region outside the plasmapause, and thus, a region of reduced concentration is observed. A further increase and then decrease in observed concentration could signify further the passage of the satellite back and forth through the plasmapause. Such an observation may be an indication that the 'torus' of the plasmapause surrounding the dayside is not smooth. This also would indicate that the convection electric field does not penetrate to lower L shells in a regular way.

5.5 Model Calculations – A Simulated Storm

5.51 Introduction

The model calculations detailed below are an initial attempt to describe the effects of a magnetic storm using the Sheffield University Plasmasphere Ionosphere Model described in Chapter 3. Obviously, to include all the phenomena and physical processes which occur during stormtimes is beyond the scope of the current model. SUPIM is a single field line model and is currently applicable only to the closed field line region of the Earth's ionosphere and plasmasphere. However, by making simple approximations to the model, it has been possible to analyse how certain features of a storm occur, specifically the refilling of flux tubes during the recovery phase from a geomagnetic storm.

As explained previously, the occurrence of a storm depletes magnetic flux tubes, as the plasmapause boundary moves equatorwards. A schematic diagram of the three phases of this process; a) *pre-storm*, b) *storm* and c) *recovery* are shown in Figure 5.10. This figure is not intended to represent the detailed physics of the storm. It merely represents the configuration of the flux tubes and the relative concentration of each region at set times before, during and after the storm, respectively. It is such an 'idealised' storm that is intended to be modelled in this study.

Certain features in the SUPIM model can be modified quite easily to simulate the changes that occur during a storm. The neutral atmosphere and neutral air wind are inputs to the model and calculated via the MSIS 86 (Hedin, 1987) and HWM 90 (Hedin et al., 1988) models respectively. Both of these have the magnetic activity Ap index as a required input. Thus, the behaviour of the neutral concentrations and the neutral wind can be approximated to represent storm conditions without further alteration to the model. However, due to the nature of MSIS 86 and HWM 90 models, the neutral atmosphere concentration and wind are averaged approximations to actual values during

disturbed periods. Thus, they may not represent the actual stormtime characteristics of the neutral atmosphere at any one period.

5.52 Model Modifications

The main modifications to the model have been made in respect of the 'storm onset' period. After storm onset, the model is left to evolve without further modification. Thus, the model storm represents depletion of plasma within a flux tube, followed by an extended period of 'quiet' during which recovery occurs. It is not intended that the results of the simulation match the DMSP observations described above. The main aim of the study is to examine the refilling process, and the chemical and physical changes that occur to the plasma within a flux tube during this time. This has been done initially, in as simple a form as possible.

The storm simulations described above have been carried out using SUPIM. Two initial sets of calculations were performed, one set where the 'model' storm was 'turned on' and the other where it was 'turned off', to provide a 'control' data set. The model storm was activated at 12:00 LT on MODEL DAY ONE, and refilling of the flux tube took place following this time. The model calculations were initially carried out for a single flux tube with an apex altitude of 8000 km, for the model day 21st June, 1991. The F10.7 and Ap indices were set to 220 and 99 respectively. The $\mathbf{E} \times \mathbf{B}$ vertical plasma drift model of Scherliss and Fejer (1999) was utilised. To provide the simplest set of conditions for the study, the axial-centred dipole magnetic field configuration was used. To simulate depletion of the magnetic flux tubes, the concentration of the O^+, H^+ and He^+ ions was reduced to 1% of their pre-storm values, at 12:00 LT. After this initial disturbance, the model is left to 'recover', and the flux tube refills. In many ways, the recovery situation is similar to that which occurs at sunrise, when the input of EUV radiation to the atmosphere rapidly increases the ion concentration. During the nighttime, the plasma content of flux tubes has fallen, and sunrise brings a sudden 'recovery' phase. Indeed, unrelated calculations using the SCTIP model (Sheffield Coupled Thermosphere Ionosphere Plasmasphere) undertaken by Wilford et al. (in press) have shown regions where He^+ becomes the dominant ion, just after sunrise.

One further set of calculations was carried out. A full run of SUPIM was performed with 112 flux tubes with apex altitudes between 150 and 40000 km. All other inputs to the model remained unchanged. The depletion of plasma was set to occur for tubes with an apex altitude less than or equal to 8000 km (L ≤ 2.26). This represented the inward boundary of the plasmapause during the model storm. Flux tubes inward of this point are unchanged by the storm, except where changes to HWM 90 and MSIS 86 produce changes from 'quiet' periods.

5.53 Results

The results shown in Figure 5.11 and 5.12 show the evolution of the modelled O^+, H^+ and He^+ ion concentrations following the simulation of a geomagnetic storm. Figure 5.11 shows the model ion concentrations from 11.30 to 13.45 LT. The stormtime reduction in ion concentration by a factor of 100 occurred at 12:00 LT. (In Figure 5.11 the times are referred to using decimal notation).
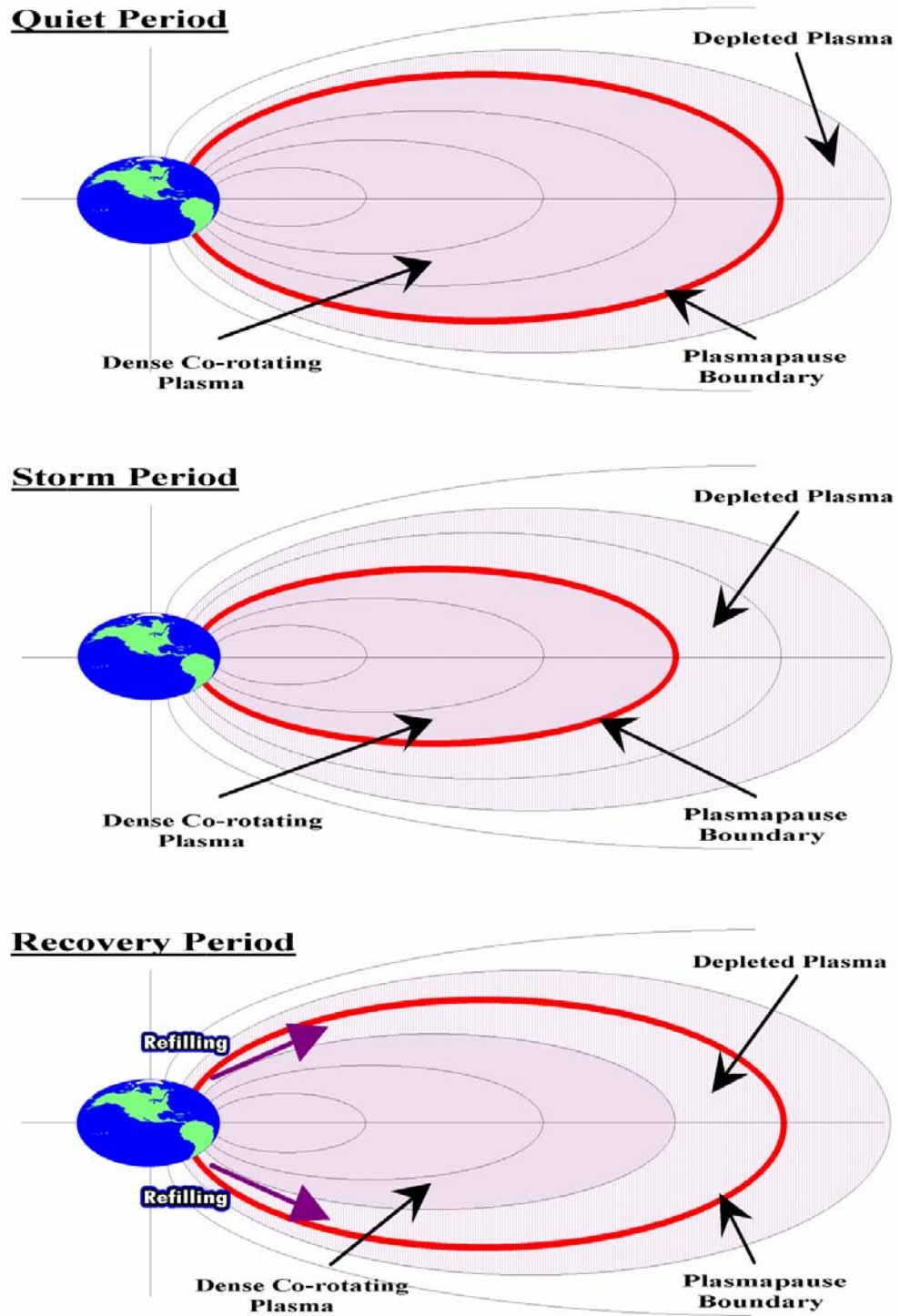
Figure 5.10. Schematic representation of the depletion and refilling of flux tubes, due to motion of the plasmapause. Refilling of the flux tubes occurs when previously convecting tubes return to co-rotation.

Since this reduction was made 'mid-model' other effects are observed in the 12:00 LT panel. At 12:00 LT, the initial reduction has a dramatic effect, particularly on the O^+ and H^+ concentrations (see Figure 5.11). Although the reduction in concentration for all ions is by a factor of 100, the O^+ concentration falls by significantly more than this in the topside region. This is due to the sudden drop in pressure supporting the topside plasma. This pressure drop causes plasma in the topside to 'collapse' back to F region altitudes, and plasma in the topside is depleted by more that the initial factor of 100. In contrast, the 'supply' of plasma to the F region ensures that the reduction in observed O^+ concentration close to this altitude at 12:00 LT is less than the initial factor of 100.

A further effect of the drop in ion concentration, is the sudden increase and importance of interhemispheric winds, particularly for the lightest ion, H^+. The strong summer-to-winter wind increases the upflow of H^+ from the northern hemisphere, and actually leads to a region of H^+ dominance around 40°N magnetic latitude which persists until 12:30 LT. It is uncertain whether such a region would occur in reality, as the ion reduction associated with an inwardly moving plasmapause is not 'instantaneous'. (Further discussion of the implications of such strong interhemispheric flow are made in Section 5.54).

As can be seen in Figure 5.12a/b/c, the reduction in ion concentration that occurs for the flux tubes inward of 8000 km apex altitude has a dramatic effect. Before the model storm onset, the O^+ ion is dominant at all altitudes above around 1600 km. The concentration of O^+ (and indeed H^+ and He^+) is also observed to be greatest in the summer hemisphere, as expected from the DMSP data. The peak H^+ concentration occurs around 1000 km altitude between 5° and 15° S. The peak He^+ concentration occurs around 700 km altitude between 15° and 35° S. The *'model plasmapause boundary'* occurs at the 8000 km apex altitude field line, and is clearly visible at 12:00 LT.

When the model storm is implemented, poleward of the model plasmapause boundary, the concentration of all three ions is dramatically reduced. This region corresponds to the low concentration plasma that moves under the influence of the magnetospheric electric field. The region inward of the model plasmapause corresponds to plasma that co-rotates with the Earth, and is, to a first approximation, unchanged by the storm. A region of He^+ dominance occurs poleward of the model plasmapause in the winter hemisphere, close to 45° S, at an altitude above around 1500 km. In this region, the H^+ concentration is at a minimum, and the O^+ concentration is also depleted.

5.54 Discussion

The observation of regions of He^+ dominance immediately following the 'model' storm is initially surprising since the ion is generally regarded as being of minor importance. However, an explanation of this result can be made by examining the chemical reactions that occur as refilling progresses. As stated previously, the refilling of depleted flux tubes approximates to the case of sunrise, when the ionisation rate increases rapidly. During this period, neutral atoms are ionised due to incoming EUV radiation, and the ion concentration in the tube increases. The chemical processes which influence the concentrations of O^+, H^+ and He^+ in the topside ionosphere, are those that occur in the F_1 and F_2 regions, before vertical transport has moved the components to regions of low chemical interaction. The main reactions are summarised in Table 5.1.
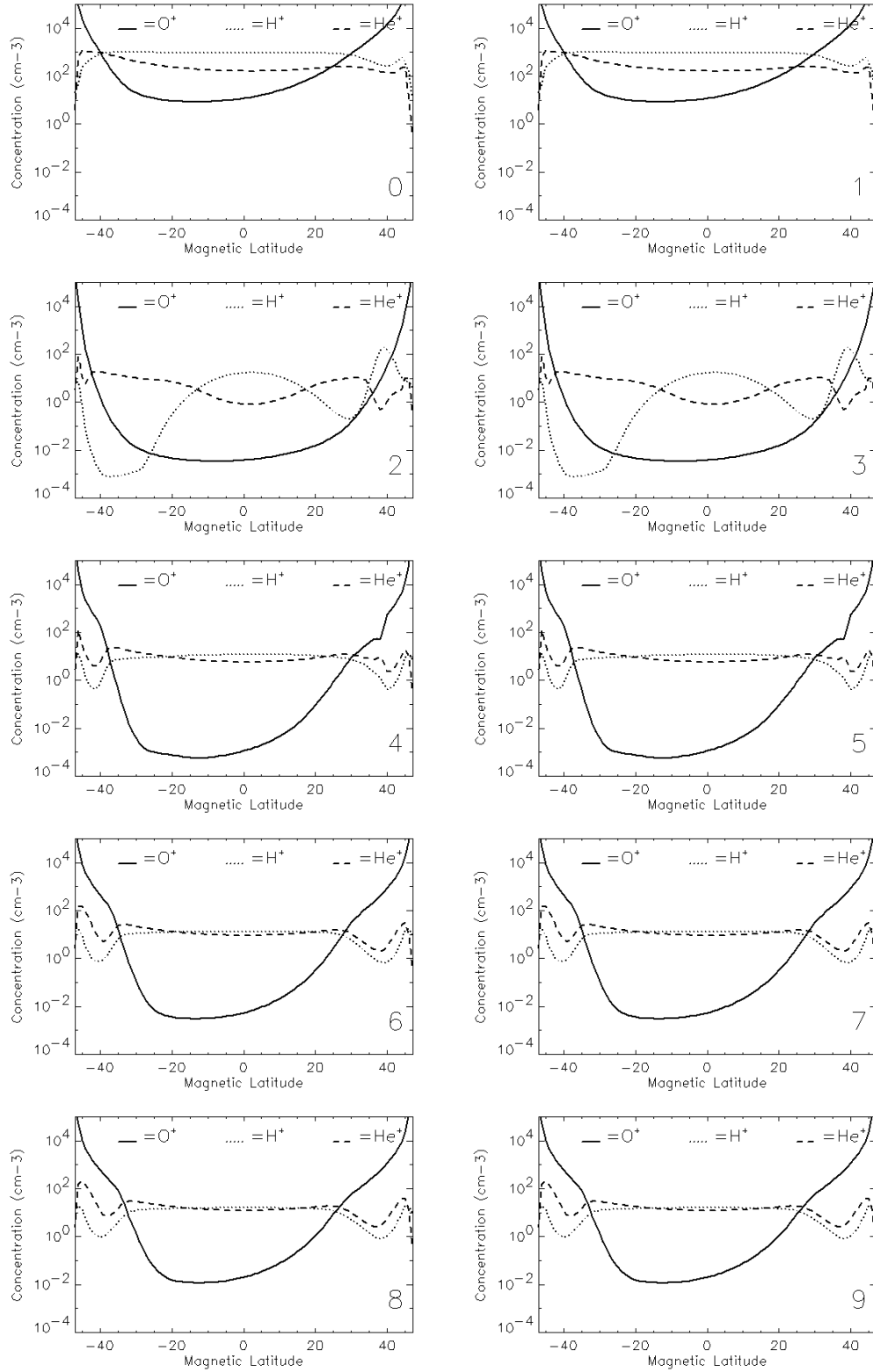
Figure 5.11. The modelled concentrations of O^+, H^+ and He^+ ions at 15 minute intervals from 11.30 LT until 13:45 LT (numbered 0 to 9). Storm onset occurred at 12:00 LT. Regions of He^+ dominance persist throughout all profiles after storm onset.
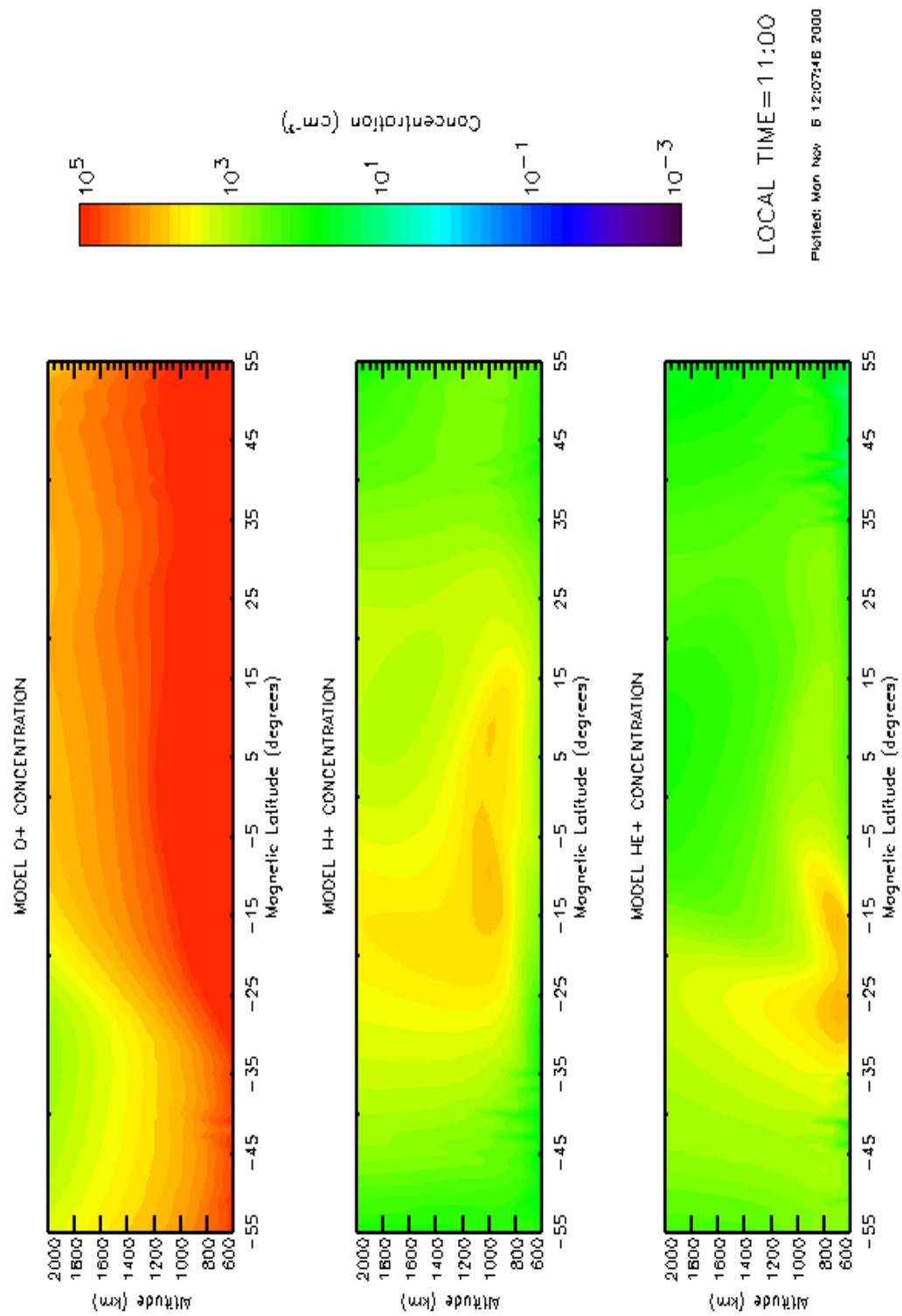
Figure 5.12a. The modelled O^+, H^+ and He^+ ion concentrations at 11:00 LT (one hour before storm onset) with respect to altitude and magnetic latitude.
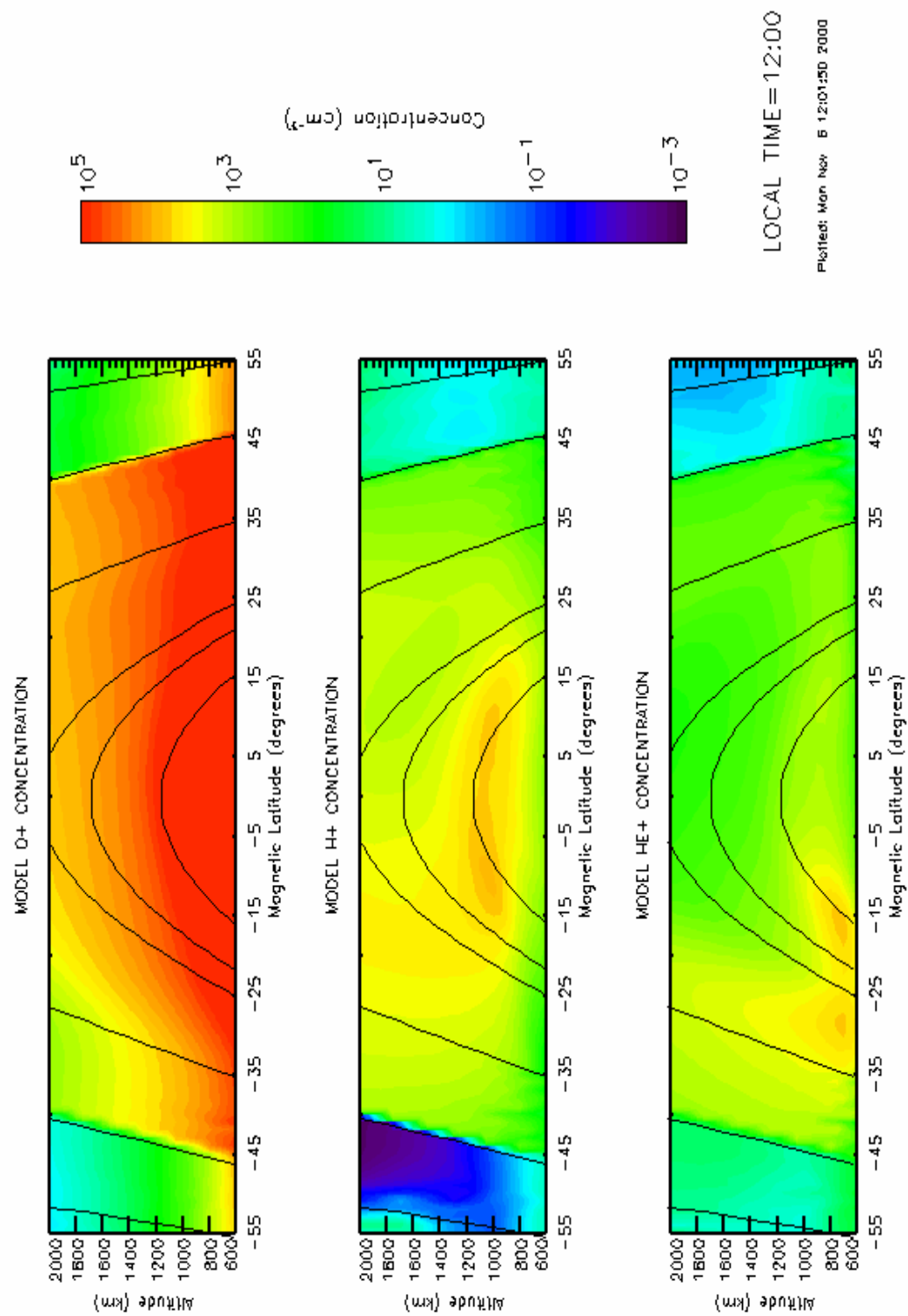
Figure 5.12b. The modelled O^+, H^+ and He^+ ion concentrations at 12:00 LT (storm onset) with respect to altitude and magnetic latitude. Selected field line locations are also shown.
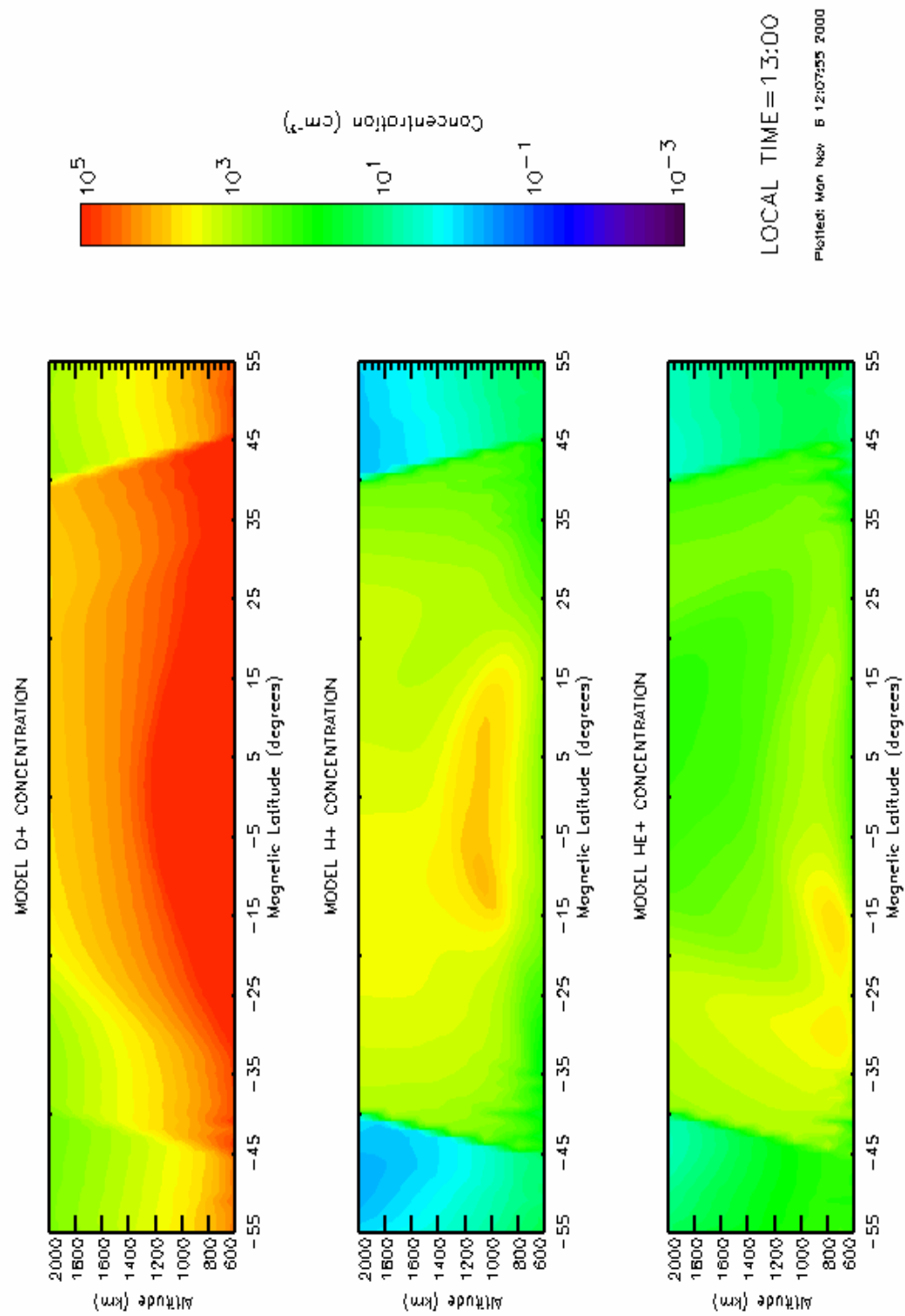
Figure 5.12c. The modelled O^+, H^+ and He^+ ion concentrations at 12:00 LT (one hour after storm onset) with respect to altitude and magnetic latitude.

The main production/loss reaction for the O^+ and H^+ ions in the topside is the charge exchange reaction between them. Almost the entire production of He^+ is via direct photoionisation. The loss reactions for He^+ only occur during the nighttime, when ions flow down the field lines to regions of increased chemical complexity.

Ion Production/Loss	Reaction
O^+ **Production**	$O + h\nu \rightarrow O^+ + e$ $H^+ + O \rightarrow O^+ + H$
O^+ **Loss**	$O^+ + N_2 \rightarrow NO^+ + N$ $O^+ + O_2 \rightarrow O_2^+ + O$ $O^+ + H \rightarrow H^+ + O$
H^+ **Production**	$O^+ + H \rightarrow H^+ + O$
H^+ **Loss**	$H^+ + O \rightarrow O^+ + H$
He^+ **Production**	$He + h\nu \rightarrow He^+ + e$
He^+ **Loss**	$He^+ + N_2 \rightarrow He + N_2^+$ $He^+ + N_2 \rightarrow He + N^+ + N$ $He^+ + O_2 \rightarrow He + O_2^+$

Table 5.1   The main production and loss processes for O^+, H^+ and He^+ ions that influence their topside ionosphere concentrations.

The observation of regions of He^+ dominance, immediately following the model storm, can be explained by a mixture of two effects. The O^+/He^+ transition altitude is typically located close to the O^+/H^+ transition altitude. This may be found around 1000 km altitude, but its location is strongly dependent upon solar activity. Thus at heights 'some way' above the DMSP orbit of 800 km altitude, He^+ is more abundant than O^+. Quiet time results from the F10 satellite indicate that for the solar activity in 1991, He^+ concentration is typically <10% of the O^+ concentration close to 800 km altitude. The modelled storm reduces the concentration of each ion to 1% of its pre-storm value.

During the refilling stage, at points above the O^+/He^+ transition altitude, the He^+ abundance is already clearly greater than the O^+ abundance. Direct ionisation of neutral helium will occur throughout the topside, and further increase the He^+ abundance. Photoionisation, and thus, production of O^+ will occur at the same time. However, the only significant source of H^+ in the topside is via the charge exchange reaction between O^+ and neutral hydrogen, with direct ionisation of neutral hydrogen being negligible. Hence, the recovery of O^+ in the topside will be suppressed, as the condition

$$n[H^+]\, n[O] = 9/8\, n[H]\, n[O^+] \qquad\qquad (5.1)$$

(Hanson and Ortenburger, 1961) is maintained.

The proposed two process mechanism which creates the modelled and observed regions of He$^+$ dominance is:

> *Process 1. Above the O$^+$/He$^+$ transition altitude, the difference in abundance between the ion concentrations will increase. He$^+$ is formed by direct photoionisation. The O$^+$ concentration is rapidly depleted due to the collapse in pressure supporting the topside plasma. Calculations show this process proceeds over a time scale of a few minutes. The O$^+$/He$^+$ transition altitude initially falls to a lower altitude.*

> *Process 2. In the F$_2$ region, O$^+$ is formed via photoionisation. However, to maintain the equilibrium between O$^+$ and H$^+$, the formation of H$^+$ suppresses the recovery of the O$^+$ ion. The charge exchange reaction proceeds quickly, but at timescales larger than those for photoionisation.*

The two processes described above are proposed as an explanation of the regions of He$^+$ dominance observed in the DMSP data. Such regions are only observed in the winter hemisphere. This is likely to be due to the effect of the neutral wind, which raises the summer F layer and depresses the winter F layer. Thus, at the DMSP altitude of 800 km, O$^+$ remains the dominant ion in the summer hemisphere. An observation of He$^+$ dominance at some altitude above 800 km in the summer hemisphere would further confirm the two processes described above.

The modelling studies of the refilling period shown in Figure 5.11 and 5.12 show a similar feature, although at an altitude around 1500 km, i.e. a higher altitude than in the DMSP observations. Reasons for this could be include inaccuracies in the HWM 90 and MSIS 86 models, which directly affect plasma concentration and transport. In addition, the abrupt reduction in model ion concentrations is unlikely to occur in a 'real' storm situation. Although the plasmapause moves equatorward rapidly, the depletion of flux tubes poleward of the plasmapause does not occur instantaneously, but is a result of convection pattern that each flux tube is subjected to.

A comparison of the Quegan et al. conditions, and the expected behaviour of the plasma during a storm also shows the observed regions of He$^+$ dominance should not be as unexpected as may be previously thought. Geomagnetic storms provide a situation where condition (i) of the Quegan et al. conditions is fulfilled. O$^+$ and H$^+$ are depleted as a result of plasma being lost, due to the inward movement of the plasmapause. He$^+$ is also initially depleted. Condition (ii) is fulfilled since at 09:00 LT, the whole flux tube is illuminated. However, during solstice the summer hemisphere section of a flux tube will have been in sunlight for longer than the winter section. Condition (iii) is fulfilled, but in a different manner than that suggested. *"Transit through a region satisfying condition (ii) ..."* occurs by definition, for storm periods observed by the F10 satellite, since all orbits studied occur close to 09:00 LT. Condition (iv) refers directly to the conditions that occur during storm activity, and is thus also fulfilled.

One further point to note is the large flow speed of the H$^+$ ion along the flux tube

(several km s^{-1}) in the period immediately following the reduction in concentration. If such a flow speed actually occurred, the plasma would be moving in excess of the local speed of sound. This would generate a shock wave of the type discussed by Banks et al. (1971) and by Singh and co-workers (Singh et al., 1986; Singh and Hwang, 1987; Singh and Torr, 1990; Singh, 1991; Singh and Horwitz, 1992). Such shocks have yet to be observed.

5.6 Conclusions and Future Work

The work presented in this chapter has been prompted by features observed in the DMSP F10 database during stormtimes. The major storm that occurred on 24th March, 1991, has formed the basis of a case study into storm effects on plasma temperature and concentration around 800 km altitude at 09:00 LT. Features in the data observed during June 1991 led to the investigation of regions of He$^+$ dominance, particularly at times of recovery from geomagnetic storms. Modelling studies have been performed in which the Sheffield University Plasmasphere Ionosphere Model was modified to simulate a storm, and the refilling of flux tubes that follow it. In many ways, the refilling of depleted flux tubes is similar to the situation during sunrise. At this time, flux tubes undergo a large rise in ion content, as the atmosphere is illuminated. Unrelated calculations, performed by Wilford et al. (in press), using the global SCTIP model, also show regions where the He$^+$ ion becomes dominant, just after sunrise.

The main results of the study relate to the introduction of a 'model' storm into the SUPIM model. By making extremely simple modifications to the model, observed regions of He$^+$ dominance made by the F10 satellite are reproduced at the correct latitude, but a higher altitude than observations. The model does not include modifications to the co-rotating plasma, and does not account for local time, seasonal or indeed, any other variables. Despite this study being a first approximation to a 'model storm', the results have led to a two stage mechanism for production of regions of He$^+$ dominance being proposed. Further modelling studies of this process are encouraged.

This study of stormtime dynamics, and particularly the proposed preferential refilling of flux tubes by He$^+$, is particularly timely, due to the recent launch of the IMAGE scientific satellite on the 25th March, 2000. The IMAGE mission is designed to provide multi-instrument studies of the inner magnetosphere, with imaging of the plasmasphere being one of the main goals. The Extreme Ultraviolet Imager (EUV) instrument on-board the satellite images the distribution of the He$^+$ ions by detecting their emission at a wavelength of 30.4 nm. Such emission is relatively easy to measure, since it is the brightest source of ion emission in the plasmasphere and because the background is negligible. This powerful technique will produce a detailed image of the plasmasphere, and the movement of the plasmapause during storms can be fully determined.

Suggestions for future work include:

♦ A full set of model calculations which examine the altitude, local time and latitudinal variation of the feature. These calculations would provide altitudinal profiles of the ion concentrations and how they changed before, during and after the model storm.

♦ An enhanced version of the 'model storm'. An extension of this current study could include a reduction in the content of flux tubes as a function of the geomagnetic activity. Also, the location of the 'model plasmapause' could be determined by either an empirical formula (e.g. Carpenter and Park, 1973), or using new results from the IMAGE satellite.

♦ A comparison of SUPIM model calculations with data from the IMAGE satellite during storm recovery periods. Such a study is highly recommended, and is considered the most promising area likely to yield a better understanding of plasmasphere dynamics during stormtimes.